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In search of the wind energy potential

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The worldwide advancement of wind energy is putting high demands on a number of underlying technologies such as wind turbine aerodynamics, structural dynamics, gearbox design, electrical grid connections, and so on. As wind is the only fuel for wind power plants, naturally, wind-meteorology and wind-climatology are essential for any utilization of wind energy. This is what we are concerned about here with a view on what has happened in wind energy potential assessments in the last 25 years where the utilization of wind turbines in national power supply has accelerated and what is the perspective for future improvements of the assessment methods. We take as the starting point the methodology of The European Wind Atlas [I. Troen and E. L. Petersen, *European Wind Atlas* (Risø National Laboratory, Roskilde, Denmark, 1989)]. From there to the global wind atlas methodology [J. Badger *et al.*, *The New Worldwide Microscale Wind Resource Assessment Data on IRENA's Global Atlas* (The EUDP Global Wind Atlas, 2015)], and finally, the perspective for the current work with the New European Wind Atlas [E. L. Petersen *et al.*, *Energy Bull.* 17, 34–39 (2014); *Environ. Res. Lett.* 8(1), 011005 (2013)] to be finalized in 2020. Published by AIP Publishing. [<http://dx.doi.org/10.1063/1.4999514>]

INTRODUCTION

Before a wind farm project takes off, there are many requirements which have to (or should) be fulfilled, such as careful planning, taking into account visual intrusion, noise issues, and impacts on wildlife; many technical matters: availability of land, roads, grids, local needs for the energy, and possibility of local involvement like the partial ownership and production. But in the end of the day, it is the wind condition on the planned site for the wind farm that almost always determine whether the farm should be built or not. Often the simple question is: Is it bankable? Admittedly, sometimes a wind farm is built for pure political reasons despite a low production prediction. The terms used in this study are defined in the “Glossary” section.

Because wind energy is becoming one of the most expanding power producing features, as is briefly presented below, the hunt for locations with a high energy potential is becoming ever fiercer.^{1–4}

An often asked question is though: Is there wind enough for a large scale accelerated development. A development which is coming to a general public understanding as necessary for mitigating global warming and the following adverse climate change. Coal, oil, and gas have to be phased out at a much faster rate than we see today, which unfortunately for some politicians in some countries act as an almost unacceptable controversy to current energy policies. But, hopefully—or indispensable—evidence must prevail over fact-resistant politicians, such as the latest news from *The Arctic Council*, Ref. 5: “The inland ice in Greenland is now melting twice as fast as ten years ago.”

According to the study *Geophysical limits to global wind power*, *Nature* 2013, Ref. 6: “there is enough power in Earth’s winds to be a primary source of near-zero-emission electric power as the global economy continues to grow through the twenty-first century. Historically, wind turbines are placed on Earth’s surface, but high-altitude winds are usually steadier and faster than near-surface winds, resulting in higher average power densities. Here, we use a climate model to estimate the amount of power that can be extracted from both surface and

high-altitude winds, considering only geophysical limits. We find wind turbines placed on Earth's surface could extract kinetic energy at a rate of at least 400 TW, whereas high-altitude wind power could extract more than 1800 TW. At these high rates of extraction, there are pronounced climatic consequences. However, we find that at the level of present global primary power demand 18 TW, uniformly distributed wind turbines are unlikely to substantially affect the Earth's climate. It is likely that wind power growth will be limited by economic or environmental factors, not global geophysical limits."

Let us illustrate this with an example, explaining what TW means:

1 TW is equal to 1000 GW, 1 GW is equal to 1000 MW, and 1 MW is equal to 1000 kW. The largest commercial available wind turbine today (2017) can extract the kinetic energy at a rate of 8 MW.

Example: An average Danish house-hold uses 4500 kW hours a year. An 8 MW turbine located in the North Sea may produce the electricity needed for approximately 8000 Danish households.

Current trends in using wind energy for national electricity supply

2016 annual Global figures from Renewable capacity statistics 2017, International Renewable Energy Agency:⁷

- In the end of 2016, the Global wind energy capacity amounts to 467 GW (up from 200 GW in 2011): Of this, 16 GW was offshore.
- The installed capacity in 2016 was 51 GW, and the investment amounted to \$112.5 billion.

2016 annual European Union figures from the Global Wind Energy report:⁸

- Wind power was installed more than any other forms of power generation in Europe in 2016. Wind power accounted for 51% of total power capacity installations.
- With almost 300 TWh generated in 2016, wind power covered 10.4% of the European (EU's) electricity demand. Figure 1 shows the wind power share and generation for ten European countries for an ordinary day.
- €27.5 billion were invested in 2016 to finance wind energy development.

Future development

According to Birol, Executive Director, the International Energy Agency (IEA), *the Paris Agreement, COP21*, calls for a total investment in wind energy in 2014–2040 of USD 3.6 trillion, corresponding to 1/3 of all investments in renewable energy. Further, USD 7.1 trillion is required for investment in transmission and distribution networks.

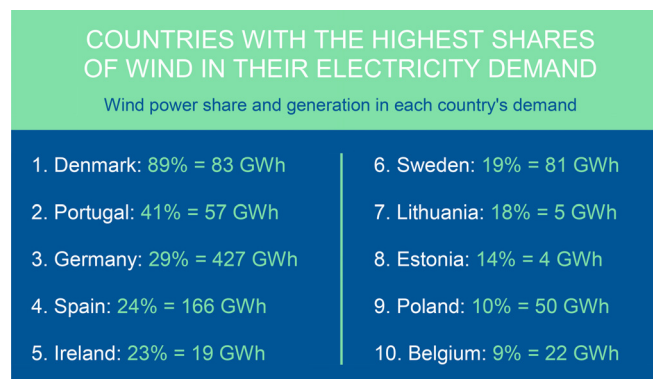


FIG. 1. The wind produced electricity on a day in March 2017. At that day, 14.9% of European (EU) electricity demand was met by wind energy. Reproduced with permission from <https://windeurope.org/> for WindEurope. Copyright WindEurope.¹⁷

Further to Birol IEA: “It is clear that wind is now a mainstream source of energy supply and will play a leading role in de-carbonisation. But becoming mainstream means also assuming new responsibilities, including ensuring the reliable and cost-effective functioning of the overall energy system and contributing to energy security. The wind industry will need to continue playing its part—using technical and financial innovation to drive costs down, improve project reliability and predictability and to make it easier to integrate wind power into electricity systems,” Ref. 8.

Further to Ref. 8: By 2030, wind power could reach 2110 GW and supply up to 20% of global electricity.

PRESENT AND FUTURE WIND RESOURCE ASSESSMENT METHODS

The European Wind Atlas

From the mid-nineteenth century, attempts were made to predict the wind conditions at specific locations for various purposes such as air pollution, building design, and planning of airports. With the beginning interest in wind energy in the early seventies, the development became focused on predicting the wind energy potential, either for regions or for single wind turbines. Many of the calculations were based on simple interpolation between meteorological stations. We jump directly to a short account of the European Wind Atlas and the wind atlas methodology, justified by the following statement from the European Wind Energy Association (now WindEurope) published in *The economics of wind energy*.⁹

“The local wind resource is by far the most important determinant of the profitability of wind energy investments. Just as an oil pump is useless without a sizable oilfield, wind turbines are useless without a powerful wind field. The correct micro-siting of each individual wind turbine is therefore crucial for the economics of any wind energy project. In fact, it is beyond dispute that, during the infancy of modern wind industry in 1975–1985, the development of the European Wind Atlas methodology was more important for productivity gains than advances in wind turbine design. The European Wind Atlas method was later formalized in the WAsP (Wind Atlas Analysis and Application Program) computer model for wind resource assessment.”

The European Wind Atlas was an international project (1981–1989) with the aim of establishing the meteorological basis for the assessment of the wind resources of the European Union. A methodology—called the *wind atlas method*—was developed, resulting in a comprehensive set of models for the horizontal and vertical extrapolation of meteorological data and estimation of wind resources using around 200 meteorological stations. The models are based on the physical principles for flow in the atmospheric boundary layer, and they take into account the effect of different surface conditions, sheltering effects due to buildings and other obstacles, and the modification of the wind imposed by the specific variations in the height of the ground around the meteorological station in question. Figure 2 illustrates the application of the wind atlas method: a procedure is followed in which the data from a meteorological station are “cleaned” from the influence mentioned above to produce regional wind climatology, and then this wind climatology is used as input to the models to produce site-specific wind climatologies in the region around the station. The models and the described methodology constituted the microscale program WAsP;¹⁰ at the time, it was used for producing the Atlas.

The publication of the overview map and the table (Fig. 3) had a profound influence on European decision makers and the general public by showing that it is possible to find locations with good wind resources almost everywhere if the right topographical settings are selected. This knowledge has important implications for any modeling of wind resources, such as meso-scale modeling: The coarser the resolution (large grid cells) the meteorological models work with, the smaller becomes the average wind resource inside the grid cell, which is because that favorable locations such as small hills and benign areas near water bodies are smoothed out. This is the underlying principle for the global wind atlas to be described in the next paragraph.

After the publication of the European Wind Atlas, it became clear that it was necessary to further develop the methodology. It works fine for not too complicated locations, but for mountainous terrain, it had its shortcomings with relatively large and unknown uncertainties. Further, most of the wind atlas methodology builds on models which are based on theories for near

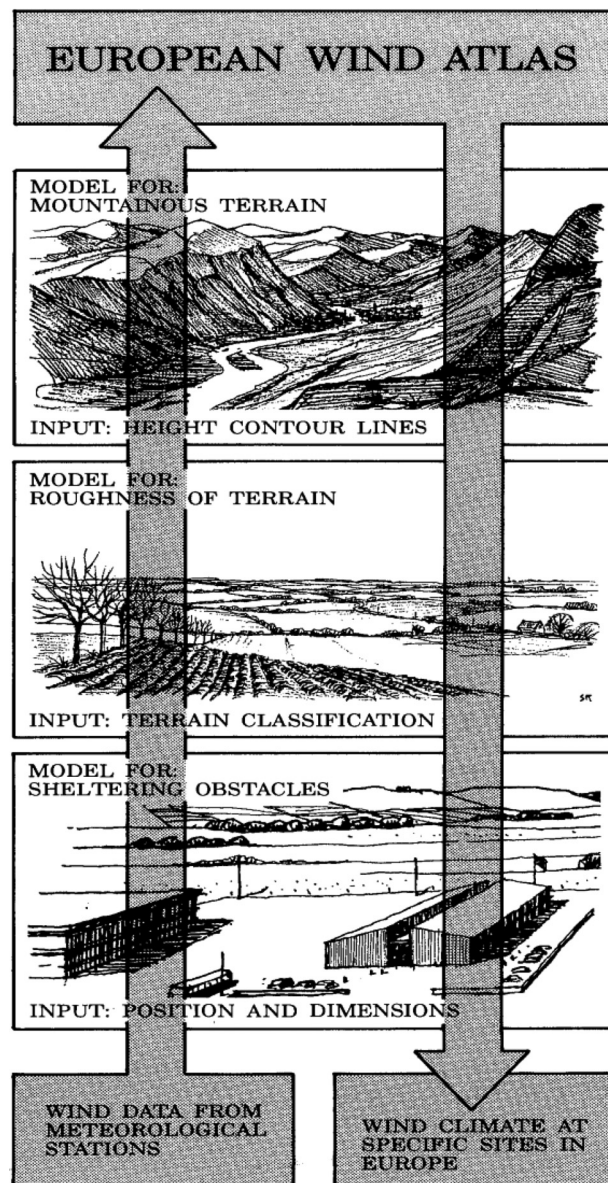


FIG. 2. The Wind Atlas methodology. Meteorological models are used to calculate the regional wind climatologies from the raw data. In the reverse process—the application of the Wind Atlas—the wind climate at any specific site may be calculated from the regional climatology. From Troen and Petersen, *European Wind Atlas*. Copyright 1989 Risø National Laboratory. Reprinted with permission from DTU Wind.¹

neutral conditions, i.e., best for good wind and overcast weather situations. But, fortunately, the developments in computers, data technology, global climate databases, and remote sensing gave rise to a continuous improvement of wind resource assessment attempting to make it applicable to almost all kind of topography and complicated wind climates.

The first major step was the combined use of mesoscale and microscale models, Refs. 11 and 12. Mesoscale models are basically the same as the models being used by the meteorological centers for weather prediction. The scale is just less, a few hundred kilometers. The procedure is that the mesoscale model uses data from the global archives, also called the reanalyse data (see below), to produce regional wind climatology, and the microscale model uses this to calculate site specific wind resources such as the power production from a wind farm. This has been developed in to a widely used method used by many research organizations and

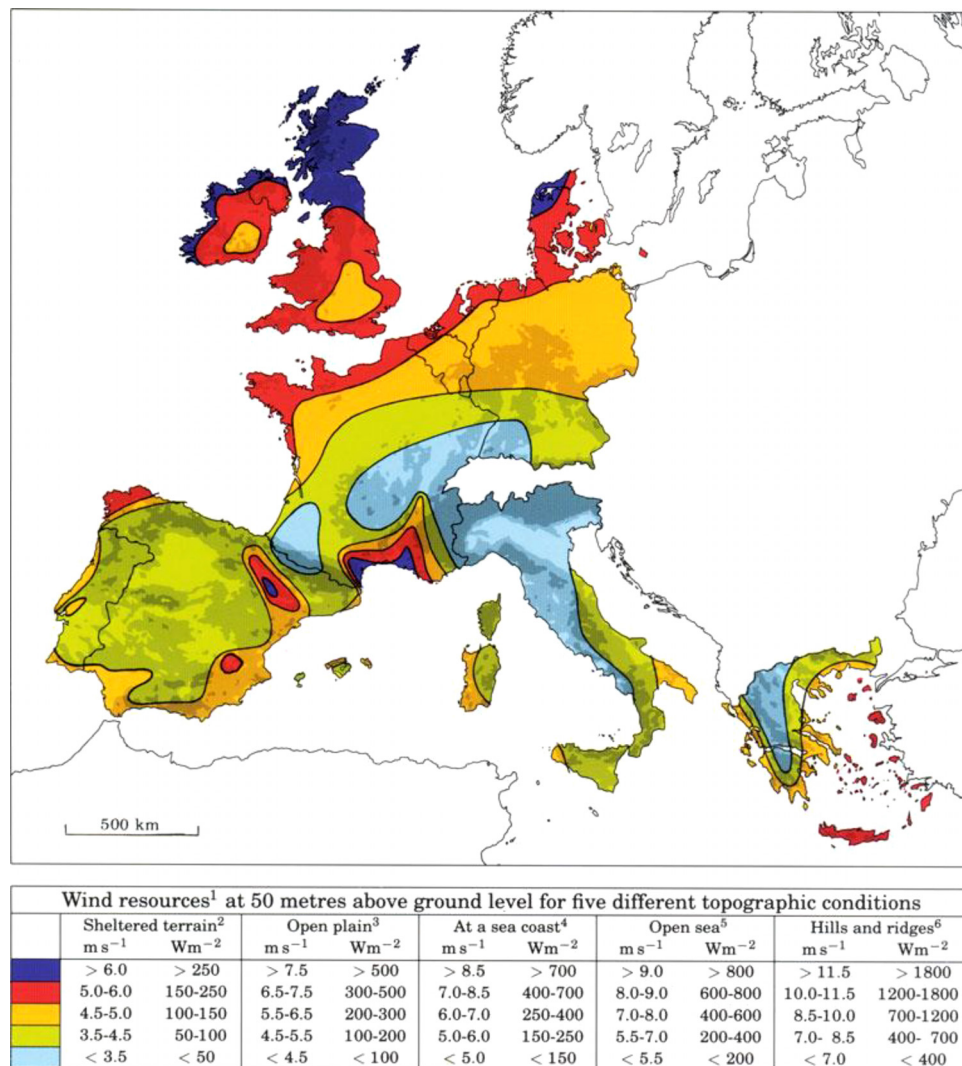


FIG. 3. Overview map from the European Wind Atlas: The large-scale variation of the European wind climate. By means of the legend, a range for mean wind speed and mean wind energy at the height of 50 m can be estimated for five topographical conditions. From Troen and Petersen, *European Wind Atlas*. Copyright 1989 Risø National Laboratory. Reprinted with permission from DTU Wind.¹

engineering companies. Often, it works well, but there are also examples on large and unexplainable deviations. An outstanding example is the Watzerath wind farm, North of Trier in Germany. Three companies calculated the production from thirteen 2 MW wind turbines and obtained almost the same result. The wind farm has now been in operation for 10 years and is producing only half of the predicted production, a catastrophe for the investors. An explanation for this large deviation is that although the terrain around looked “computational,” a combination of complicated orography and patchy woodland took the consultants by surprise, and up to today, no models have been able to reproduce the power output from the wind farm. This is not the only example on problems with contemporary models resulting in an urge for initiating the “large leap” in the improvement of the wind resource assessment methodology. Therefore, the European commission and a number of European countries have launched the project “The New European Wind Atlas (NEWA)” with one of the aims to reduce the uncertainty in wind energy potential calculations. Before we proceed to a description of the work with the New European Wind Atlas and the perspective for its use, we will give an account of a newly developed methodology for establishing the worldwide wind energy potential: The global wind atlas.

THE GLOBAL WIND ATLAS

The fundamental idea behind the global wind atlas methodology follows what is depicted in the overview map from the European Wind Atlas. Namely, even in areas where the overall wind energy potential is low, it is often possible to find locations with a sufficient potential, mostly due to orographic effects.

The global wind atlas is part of an international collaboration. It has come about in the framework of the Clean Energy Ministerial (CEM) (<http://www.cleanenergyministerial.org/>) and in particular, the CEM Working Group on Solar and Wind technologies and IRENA's Global Atlas for Renewable Energy (The International Renewable Energy Agency: <http://irena.masdar.ac.ae/>).²

Overview of the methodology

The global wind atlas uses a downscaling process, but there is no mesoscale model involved; hence, the process is not dynamic.

It begins with large scale wind climate data and ends with microscale wind climate data. The large scale wind climate data are provided by atmospheric reanalysis data, from meteorological centers around the world. These data are on a grid with a spacing of about 50 km depending on the dataset. A generalization process is performed on these data. The result is a set of generalized wind climates which have the same spacing as the reanalysis data that were used to create them. Next, this set of generalized wind climates are applied in microscale modelling systems over the globe (apart from poles and far offshore ocean areas). The modelling process is made up of a calculation for the local wind climates every 250 m at three heights, 50, 100, and 200 m. So, on a 250 m grid, there is a local wind climate estimation. Local wind climate characteristics are aggregated up to a 1 km grid. Datasets and tools for analyzing statistics based on the 250 m grid values are available on the global wind atlas website (globalwindatlas.com/). Further, a search engine is used for a more comprehensive description of the global wind atlas. Here, we will finish with an illustrative example which is taken directly from Ref. 2. In this reference it is stated that: "The correct usage of the global wind atlas dataset and tools is for aggregation, upscaling analysis and energy integration modelling for energy planners and policy makers. It is not correct to use the data and tools for wind farm siting."

Example of the global wind atlas methodology

Figure 4 shows the wind power density at 50 m for a $50 \text{ km} \times 50 \text{ km}$ area modelled at two different resolutions, namely, 2.5 km and 100 m. As the resolution increases, features in the terrain become better resolved. Resolved hills and ridges give rise to increased wind speeds.

As wind power density is a function of wind speed cubed, the impacts of the resolved terrain features are significant. For the $50 \text{ km} \times 50 \text{ km}$ area, the area mean wind power density is estimated to be around 320 Wm^2 by the modelling at a resolution of 2.5 km. For the 100 m resolution modelling, the mean power density is around 505 Wm^2 , i.e., an increase of 50% compared to the lower resolution estimates. The comparison becomes more striking when the distribution of the wind power density is considered. Consider this: we split the $50 \text{ km} \times 50 \text{ km}$ into two areas; the first area where the wind power density is below the median value, and the second area where the wind power density is above the median value. Next, we calculate the mean wind power density in the second higher wind area; the 2.5 km resolution modelling gives 380 Wm^2 , whereas the 100 m resolution modelling gives 640 Wm^2 , an increase of nearly 70%. The impact gets stronger as we look at the even windier areas. As wind turbines will be deployed at the favorable sites, it is important to be able to capture the distribution of wind power density due to terrain features, and this is only possible by consideration of high resolution effects. As one concentrates on the most favorable areas, the wind power density increases. The search for the most favorable sites for wind farms leads directly to "The New European Wind Atlas" section.

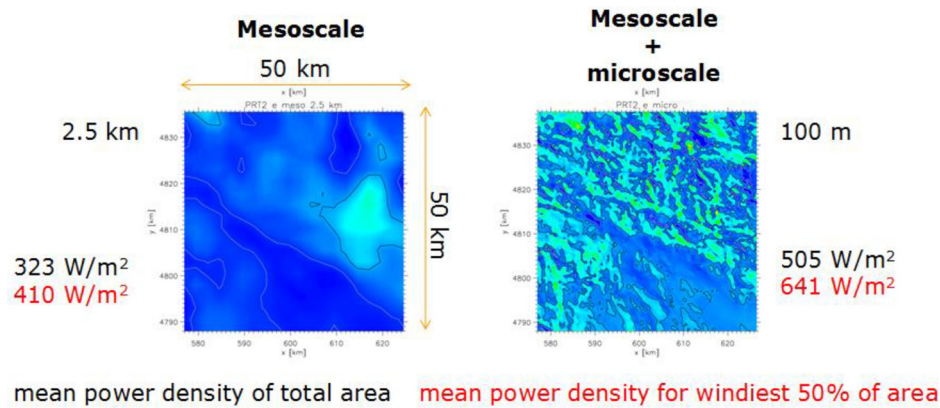


FIG. 4. Wind power density calculated at 50 m above the surface for a 50 km \times 50 km area at two different resolutions, (left) 2.5 km and (right) 100 m. The color scale used in each map is the same. Dark blue denotes small values and bright green and yellow denote large values. The mean power density for the area is given in black. The mean power density for the windiest 50% area is given in red. Courtesy Jake Badger, DTU Wind.¹⁸

THE NEW EUROPEAN WIND ATLAS (NEWA)

As already mentioned in the previous paragraphs, today, a number of well-established models and methodologies exist for estimating resources and design parameters, and in many cases, they work well. This is true if good local data are available for calibrating the models or for verification. But the wind energy community is still hampered by many projects having large negative discrepancies between calculated and actual experienced resources and design conditions (e.g., the Watzerath case mentioned above) (<http://www.neweuropeanwindatlas.eu/>).

However, when such significant discrepancies are found, no well-established methods exist to correct the situation. Discrepancies can be introduced at any point in the modeling chain, from insufficient input data to deficient physics and resolution in any of the models, model linking issues, insufficient resolution or errors in surface topographical data such as terrain heights and land cover data.

Therefore, it has been decided at a European Union level to launch a project “The New European Wind Atlas” aiming at reducing overall uncertainties in determining wind conditions: reduction in uncertainties to less than 3% for a flat homogenous terrain and to less than 10% for any terrain. The project stands on three legs: A data bank from a series of intensive measuring campaigns, a thorough examination and redesign of the model chain from global, mesoscale to microscale models, and the creation of the wind atlas database, all illustrated in Fig. 5. Although the project participants come from the EU member states, it is open for global participation through test benches for model development and sharing of data, climatologically as well as experimentally. The project was started in May 2015, and there is a substantial partnership with the US. The new European Wind Atlas will be ready for use in 2020 (see Refs. 13, 14, and 16).

The Atlas is developed with the aim to be used as a standard for site assessment. It is based on improved modelling competencies on atmospheric flow, which, together with the guidelines and best practices for the use of data, should become a key tool not only for manufacturers and developers but also for public authorities and decision-makers, with the reduced overall uncertainties in determining wind conditions.

The work with the Atlas involves the development of new dynamical downscaling methodologies as well as improvements and extensions of the models involved with a high temporal and spatial resolution. The NEWA project aims at a multi-model ensemble philosophy which needs to be theoretically well founded including the downscaling from the meso- to microscale, for example, including atmospheric stability.

The Atlas work takes advantage of newly created long term datasets (reanalyse, topography and land use) and will incorporate comprehensive information about wind conditions for all stages of wind projects’ life-cycle.

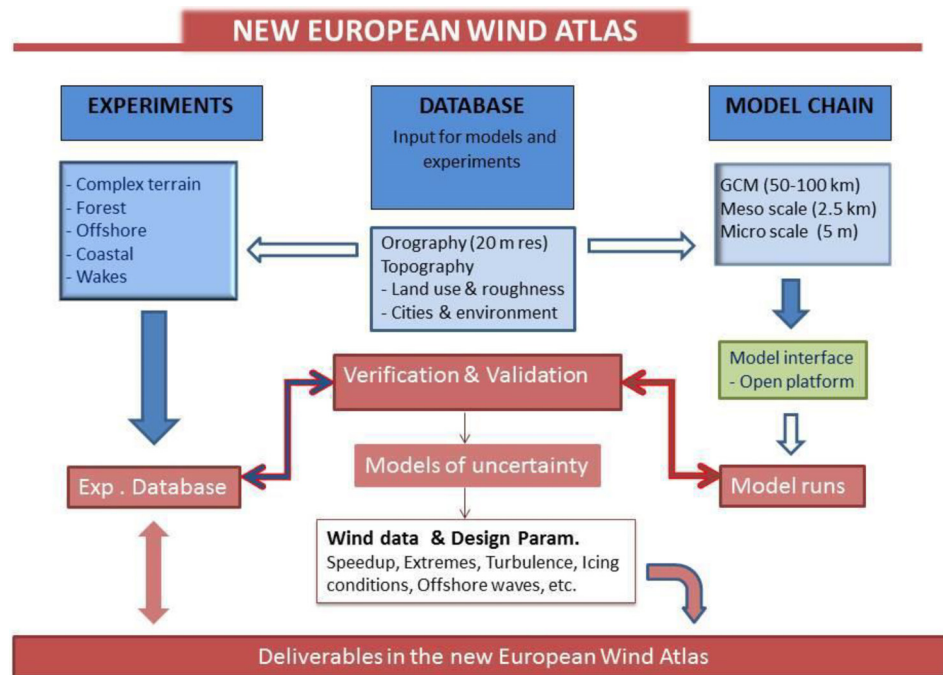


FIG. 5. The actions and final deliveries of the NEWA project. The three columns illustrate the main activities in the NEWA project. Database: Creation and publication of a European wind atlas in electronic form. Model chain: Development of dynamical downscaling methodologies and open-source models. The model chain spans from Global models (GMS) covering the whole Globe and a numerical resolution of 50–100 km to Mesoscale models covering regions, for example, part of Scandinavia with a numerical resolution of 5–2 km and finally microscale models with a resolution of a few meters. Experiments: Measurement campaigns to validate the model chain used in the wind atlas, e.g., the Perdigo experiment (Fig. 6). Reprinted with permission from Lundtang *et al.*, Energy Bull. 17, 34–39 (2014). Copyright 2014 DTU Wind.³

Overall, the new Atlas will provide a unified high time and space resolution and freely available dataset of wind energy resources in Europe. The statistics in the atlas will cover Europe with a resolution of 20–30 m in at least 10 wind turbine relevant heights. This dynamic downscaling is built on at least 10 years of mesoscale simulations with a resolution of 2–3 km. These mesoscale data will be publicly available as 10 years long hourly time series.

The area coverage is the EU countries and a group of Associated Countries, including 100 km offshore plus the Baltic and the North Sea. In addition to the wind resource information, the new Atlas will give measures of wind variability, wind power predictability from day-ahead to decadal, and parameters for wind turbine design.

The actions and final deliveries of the NEWA project are further described below.

Development of a high-value data bank from a series of wind measurement campaigns

Current tall wind turbines are often placed in remote areas on steep ridges and in forested terrain.

This project aims to provide a detailed and accurate description of the wind flow at selected sites in such terrain based on well-instrumented meteorological field experiments covering a wide range of topographical and climatological conditions. The produced data will be publicly available and can be used by private and public partners to develop models and engineering tools.

A number of unprecedented experiments are currently being executed and planned.

An example is the Portuguese Perdigo meso-microscale experiment carried out in a landscape with two parallel mountain ridges. It is illustrated in Fig. 6, indicating a huge number of meteorological masts. Lidars and a huge number of instruments are extensively used. For more information on the experiments, see Refs. 13 and 14.

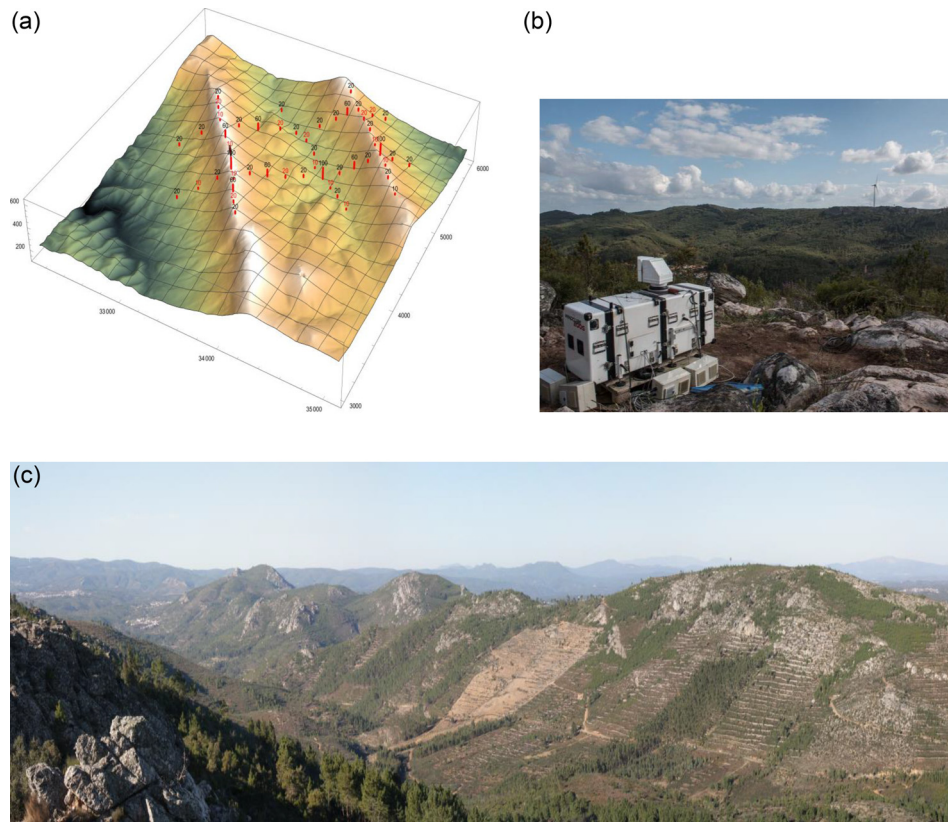


FIG. 6. The Perdigao, Portugal experiment (Refs. 13 and 14). Upper left: The extraordinary high intensity of meteorological masts is shown. Upper right: A laser anemometer system. Below: The Portuguese Perdigao double ridge. Courtesy Jakob Mann, DTU Wind (upper left figure) and Michael Courtney, DTU Wind (the two pictures).¹⁹

Development of the methodology and improvement of advanced models for wind farm development, wind turbine design conditions, spatial planning, and policy promotion (the model chain)

This project aims to determine the wind conditions with a very low uncertainty when planning wind farms. Hence, it is necessary to develop the essential models (based on results from the experimental campaigns) so that they are tailored to the Wind Atlas and can provide results with accuracy unseen today. How to link the wind resource information provided by the micro- and meso-scale models is an intense research area—NEWA aims to establish a new methodology for the coupling between the two, which will be open-source knowledge contributing to innovative research in wind energy.¹⁵

Creation and publication of a European Wind atlas (database on wind data, environmental, and other constraints)

The new European Wind Atlas database to be developed will include: wind resources and external design parameters and their associated uncertainty; the level of predictability for short to long term forecasting; guidelines and best practices for the use of data (particularly relevant for micro-siting).

The Atlas will cover all EU Member States and a group of Associated Countries, as well as their exclusive economic zones and restricted areas (Natura 2000 sites, military areas). The interface of the NEWA database will include an interactive web-based map with a response.

Verification and estimation of uncertainty

An uncertainty map will calculate the confidence of the Wind Atlas and the intensity at which *in situ* measurements must be employed before the development of a wind farm. The

uncertainty will be verified by a large number of wind climate data and wind farm production data covering the total area including offshore areas. The experimental results will also be used especially for theoretical work, developing new procedures for uncertainty calculations.

It is the intention of the European Commission, the participating member countries, and their research organizations that the NEWA project will be innovative and will bring significant scientific and technological progress beyond the state-of-the-art in the area of wind resource assessment.

Recent developments are essential for fulfilling this goal: New advanced numerical meteorological Models: global, mesoscale, and microscale; New detailed global datasets (reanalyze); the advances in remote sensing technology, especially the use of lasers; last but not the least, the ever increasing computer power and data storage possibility.

GLOSSARY

Climatology: The average weather experienced at a place in the course of some chosen run of years.

Downscaling methods: The concept of downscaling large-scale analysis and forecasts of weather and climate such that small-scale features are estimated based on input about large scale structures of the atmosphere. Two concepts are used: Dynamical and Statistical.

Dynamic downscaling: The use of mesoscale meteorological models to generate high resolution climate statistics for a specific region and period of time based on, e.g., the Global data archive.

Global data archive: Global or near global covering climatological and topographic data.

Grid resolution: The physical laws that govern the motions of the atmosphere are solved by a numerical model at grid points in a three dimensional mesh. The distance between the grid points is the grid resolution. The physical resolution, however, is about 5 times the numerical resolution. Hence, in a numerical grid of 2 km, only atmospheric motions of a scale larger than 10 km can be resolved.

Hub height: Height above the ground at the centre of the rotor—usually the same as the tower height.

Lib files: Tables of the two Weibull parameters given for a number of wind direction sectors, heights above ground, and terrain roughness classes, used in the Wind Atlas methodology.

Lidar: Light Detection and Ranging. Wind measurement device based on laser – Doppler technology.

Mesoscale model: Numerical meteorological models based on the full set of dynamical fluid equations, usually covering a region of a few hundreds of kilometers and a grid resolution of 2–10 km. An example is the PSU/NCAR mesoscale model (known as MM5) which is a limited-area, non-hydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale atmospheric circulation.

Microscale model: Numerical flow models that can be based on the dynamical fluid equations, e.g., CFD models, or on a linearized version of the fluid equations. An example of a linearized flow model is the BZ (Bessel-zooming-grid) model in WAsP.

Orography: The height variations of a terrain.

Reanalysis dataset (Global Data): Time series of the large-scale meteorological situation covering decades. These datasets have been created by assimilating measurement data from around the globe in a dynamical consistent fashion using large scale numerical models. The primary purpose for the generation of the dataset is to provide a reference for the state of the atmosphere and to identify any features of climate changes. For wind energy, the application of the dataset is a long term record of large scale wind conditions.

Regional resource assessment of wind energy resources means estimating the potential output from a large number of wind turbines distributed over a region. Ideally, this results in detailed, high-resolution and accurate resource maps, showing the wind resource (yearly and seasonal), the wind resource uncertainty, and areas of enhanced turbulence.

Short term prediction: Prediction of the power output from a wind farm hours and days ahead. The prediction is based on a mesoscale forecast model combined with a microscale model—the model chain concept.

Siting is a process that includes estimating the mean power produced by specific wind turbines at one or more specific locations. Proper siting of wind turbines with respect to the wind resource requires proper methods for calculating the wind resource, the turbulence conditions, the extreme wind conditions, and the effects of rotor wakes.

The Wind Atlas method: the conventional method used to produce estimates of wind resources on national scales is to analyze wind measurements made at a number of sites around the country as in, for example, the European Wind Atlas (Ref. 1). In order for this method to work, there needs to be a sufficient quantity of high quality data, covering the country.

ACKNOWLEDGMENTS

Jakob Mann and Jake Badger both from DTU Wind Energy and responsible for the new European Wind Atlas and the Global Atlas, respectively, are thanked for providing materials for the projects.

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